NASA-CR-200286

CASI

Cloud-Climate System Interactions

NASA Grant NAG-2039

1995 Annual Report

Principal Investigator:
Albert Arking
Department of Earth and Planetary Sciences
Johns Hopkins University
Baltimore, MD 21218
e-mail: arking@aa.gsfc.nasa.gov
TEL: 301-299-2478
FAX: 301-299-2479

March 8, 1996

1. Objectives

The aim of this research task is to understand the interrelationship of clouds, water vapor (WV), sea surface temperature (SST), and the large-scale circulation, with specific emphasis on their effect on the energy balance of the climate system. The ultimate goal is to determine whether these processes have a feedback effect on the climate system's response to "external" perturbations, such as changes in carbon dioxide and other greenhouse gases. Specific questions to be answered include:

a. How do the Hadley and Walker circulations change in response to changes in the sea surface temperature field, and how does this affect the cloud distribution?

b. Do these circulations intensify or weaken in the presence of high level clouds?

c. What is the role of water vapor and water vapor transport in the cloud-SST relationship?

While this research was going on, a new issue arose with the publication in Science of 3 papers that purport to show a major discrepancy between radiative energy transfer codes used in climate models and observations of radiative fluxes at the surface. The discrepancy indicated that a lot more solar energy is absorbed in the presence of clouds than under cloud-free conditions, and is commonly referred to as "anomalous" cloud absorption. Since our work involves the analyses of data sets that include the output from general circulation climate models and observations of clouds and radiative fluxes, we decided to carefully examine this issue, using the data sets in our possession. It is an extremely important issue because it bears on the question of how much energy is absorbed in the atmosphere versus how much is absorbed by the surface, and the relative roles of the atmosphere and oceans in driving the climate system.

This status report summarizes the research activities with respect to the main objective of this research task in Sec. 2, and with respect to the anomalous cloud absorption problem in Sec. 3. Papers published, in press, or submitted for publication in scientific journals, and unpublished papers in proceedings, are listed in Sec. 4. An outline of future work is presented in Sec. 5.

2. Interrelationships of Clouds, WV, SST, and the large-scale Circulation

We utilized monthly mean observations of variables associated with clouds, water vapor, and the large scale circulation to study the relationships of these variables to changes in sea surface temperature. The observations include top-of-the-atmosphere fluxes from the Earth Radiation Budget Experiment (ERBE); cloud amount, cloud height, and cloud optical thickness from the International Satellite Cloud Climatology Project (ISCCP); total column water vapor from NOAA TOVS; and sea surface temperatures from NOAA based on a blend of AVHRR and in situ measurements. The data consist of monthly averages on a 2.5° latitude by 2.5° longitude grid, extending from 150E to 90W and 25S to 25N, for the period February 1985 through January 1989.

A previous analysis of a part of that data set has shown that in the western tropical Pacific cloud cover and its radiative effects change dramatically when and where sea surface temperatures exceed ~300 K (Arking and Ziskin 1994). The changes involve an increase of high level clouds with increasing sea surface temperature—substantially increasing total cloud cover, optical thickness, and mean cloud height (the last revealed by the decrease in mean cloud temperature). Further analysis showed that before the high level clouds are fully developed, there is a massive increase in upper tropospheric moisture with increasing sea surface temperature—about an order of magnitude larger, in a relative sense, than the moisture increase in the boundary layer. That study was based on point-to-point correlations, where the monthly mean value of a variable in each grid box was treated as an independent point, and the domain was restricted to the western tropical Pacific (150E–180E).

In order to learn what is happening on a larger scale, and to take into account remote relationships (i.e., how changes at one spatial grid point might be related to changes at another grid point), we utilized principal component analysis, showing changes in the spatial patterns across the entire tropical Pacific (150E–90W). Since we are interested in climate change, we removed the very large variations associated with the seasonal cycle by subtracting from the value at any grid point in any month the mean over the four-year period for that grid point and month. This yields what is called the interannual anomaly. The principal components of each variable are the eigenfunctions of the covariance matrix, derived using standard numerical procedures.

Preliminary results from this analysis were presented at the Symposium on the Regulation of Sea Surface Temperatures and Warming of the Tropical Ocean-Atmosphere System, held January 1995 in Dallas, Texas, as part of the 75th Annual Meeting of the American Meteorological Society. A written report appears in the published proceedings of that symposium. Preliminary findings from that study can be summarized as follows.

There is a strong coherence amongst the 1st principal components of all of the variables, all following the large swing in the Southern Oscillation that took place during that period. The changes that take place over the course of the Southern Oscillation involve significant changes in the energetics of the system, including an effect on the vertical distribution of heating rate. In the western portion of the domain, increases in cloud cover involve radiative cooling of the ocean surface by ~40 W m^{-2} with a heating of the atmosphere (mostly confined to the upper troposphere) of comparable magnitude, in agreement with Ramanathan and Collins (1991) and Arking and Ziskin (1994). Such changes in the vertical heating profile tend to reduce convective instability.

We also find a decrease in clear-sky outgoing longwave radiation as the El Niño phase of the Southern Oscillation builds up. This occurs despite the increasing sea surface temperature, and we believe it to be a manifestation of an increase in upper tropospheric moisture. In addition, as the El Niño develops, there is a marked reduction in the large zonal gradient of sea surface temperature that is typically present in that region. A reduction in the sea surface temperature gradient would be expected to weaken the large-scale circulation (Lindzen and Nigam 1987), and thereby reduce the low level convergence, which is an important source of moisture in the western tropical Pacific.

Thus, there appear to be three things going on over the western tropical Pacific during El Nino development: (1) increase in high level clouds, with its stabilizing effect on convection; (2) decreasing clear-sky OLR with increasing sea surface temperature, indicating a massive increase in upper tropospheric moisture; and (3) near-disappearance of the strong zonal sea surface temperature gradient, with its implications for the large-scale circulation.

3. Anomalous Cloud Absorption

Three papers published in Science in early 1995 (Cess et al 1995; Ramanathan et al 1995; Pilewskie and Valero 1995) have reported a large inconsistency between observations of solar radiative fluxes in the atmosphere and the numerical models used to compute such fluxes. The inconsistency is with respect to the difference between the average radiative flux under all cloud conditions and an estimate of what the flux would be under "clear-sky" conditions, and their implications concerning atmospheric absorption. Measurements of solar flux were made at the top of the atmosphere, from satellite sensors, and at instrumented surface sites. They were also made from coordinated aircraft flying above and below clouds. The investigators found that the difference between average and clear-sky fluxes is much higher at the surface, or below the cloud layers, than at the top of the atmosphere, or above the cloud layers. Their results imply that clouds cause substantially more absorption of solar radiation by the atmosphere, and less by the surface, than one would calculate with numerical radiative transfer models. The models indicate that the average versus clear-sky difference should be generally about the same above and below the cloud layers—which would be the case if clouds were weak absorbers of solar radiation.

The implications for radiative transfer theory are enormous. We conducted some numerical experiments with the Chou radiative transfer code, which is based on absorption/scattering ratio observations inside clouds. We found that one would have to increase the observed absorption/scattering ratios by a factor ~40, in order to match the above interpretation of surface flux measurements. These results were published in August in Geophys. Res. Lett. (Chou et al 1995).

We then carefully examined the methodology used by Cess et al (1995) and Pilewskie and Valero (1995). (The results of the 3rd paper, Ramanathan et al 1995, are based on educated guesses, with admittedly large uncertainties, and they admit that their conclusion about anomalous cloud absorption is not firm.)

We noted that the Cess et al and the Pilewskie and Valero results rest on two methods that were used in both investigations, and both methods led to the same conclusion, that clouds significantly affect the amount of solar radiation absorbed in the atmosphere. Our examination found that these investigations neglected to take into account that their measurements of surface flux (or, in the case of Pilewskie and Valero, the aircraft measurements below cloud level) are near-instantaneous measurements made at a single point in space, not averages over large areas or long periods of time. Measurements under such circumstances are subject to a large variation that depends on the position of the clouds relative to the sun when the measurement is made: the flux can be higher or lower than the clear-sky flux, depending on whether the clouds block or do not block the direct rays of the sun. Measurements above cloud level are not subject to that effect. Because of this asymmetry between measurements above and below cloud level (e.g., downward fluxes above cloud level are generally a maximum when there are no clouds, but not so for downward fluxes below cloud level) their methods lead to a bias in which they overestimate atmospheric absorption in the presence of partial cloud cover. This examination of the methodology is described a paper to appear in Geophys. Res. Lett. (Arking et al 1996).

We next decided to see what discrepancies there are between models and observations, based on the data sets we had assembled for our work on the cloud/WV/SST/circulation study. We already had observational data sets of cloud variables and top-of-the-atmosphere radiative fluxes, and we had the output of a general circulation model that was run with space-time assimilation of daily observations of temperatures, humidity, winds, and sea level pressure, for the corresponding period (GEOS-1, described by Schubert et al 1993). In order to determine the observed atmospheric absorption, we needed observations of surface radiative flux. For that we used surface observations known as the Global Energy Balance Archive (GEBA, described by Ohmura and Gilgen 1993), which were made available with collocated ERBE and ISCCP observations by the NASA Langley Surface Radiation Budget Project.

With the above data sets, we were able to compare observed and model-determined atmospheric absorption. The results confirm that there is an overall deficit in the model of 25–30 watts per square meter in the amount of solar energy absorbed by the atmosphere. But in sharp contradiction with the 3 papers in Science, clouds are found to have little or no effect on atmospheric absorption, a consistent feature of both the observations and models, of which the one analyzed here is typical. Water vapor is found to be the dominant influence on atmospheric absorption, suggesting that to correct our models, we need to improve the parameterization of water vapor absorption and, perhaps, look for additional sources of absorption in the clear atmosphere. These results appear in a paper submitted to Science

(Arking 1996).

We also compared atmospheric absorption and the influence of clouds on atmospheric absorption based on other observational data sets and other models. The results are similar, and are presented in a paper submitted to Bull. Amer. Meteor. Soc. (Li et al 1996).

4. Publications

Published or in press, refereed journals:

"The Effect of Clouds on Atmospheric Solar Heating," M. D. Chou, A. Arking, J. Otterman, and W. L. Ridgway, *Geophys. Res Lett.*, 22, 1885–1888, 1995.

"On Estimating the Effects of Clouds on Atmospheric Absorption Based on Flux Observations Above and Below Cloud Level," A. Arking, M.-D. Chou, W. L. Ridgway, *Geophys. Res. Lett.*, in press, 1996.

"A Case Study of Cirrus Layers with Variable 3.74-micron Reflection Properties in the First FIRE Experiment, 2 November 1986," C. M. R. Platt and A. Arking, *Theor. Appl. Climatol.*, in press, 1996.

Appeared in proceedings:

"Interactions Involving the Large-scale Circulation, High Level Clouds, and Sea Surface Temperatures in the Tropical Pacific," Albert Arking, *Symposium on the Regulation of Sea Surface Temperatures and Warming of the Tropical Ocean-Atmosphere System*, Preprint Volume, 75th AMS Annual Meeting, Dallas, TX, Jan 15-20, 1995.

"Shortwave Radiation Absorption in Clear and Cloudy Atmospheres," Albert Arking, *Proceedings of the Workshop on the GEOS-1 Five-Year Assimilation*, NASA Tech. Memo. 104606, v. 7, Greenbelt, MD, March 6-8, 1995.

Submitted for publication:

"Absorption of Solar Energy in the Atmosphere: Discrepancy Between a Model and Observations," Albert Arking, *Science*, submitted, 1996.

"On Solar Energy Disposition: A Perspective from Surface Observations, Satellite Estimation, and GCM Simulation," Z. Li, L. Moreau, and A. Arking, *Bull. Amer. Meteor. Soc.*, submitted, 1996.

5. Future Work

During 1996, work will continue in two areas:

- *Interrelationships of Clouds, WV, SST, and the Large-scale Circulation*

  To understand the changes in cloud variables and water vapor that are taking place during the course of the Southern Oscillation, and determine their influence, if any, on the Southern Oscillation and other phenomena of the tropical Pacific, requires further study—especially bringing into the analysis the dynamic terms. These terms will come from the GEOS-1 data set. Because the Southern Oscillation signal appears in almost of the variables, it will be difficult to determine cause and effect. However, any hypotheses concerning cause and effect that are inferred from this analysis can be tested with the GEOS model. Such tests will be carried out in collaboration with colleagues who are working intimately with that model.

In order to ascertain that the relationships coming out of the analysis involving the dynamical terms are driven by the observations that are assimilated into the model, and not artifacts of the model, we will acquire the output from the NMC re-analysis for the same time period and compare results from the two data sets.

- *Discrepancy in Atmospheric Absorption Between Models and Observations*

  Our models indicate that about 22% of the solar energy is absorbed in the atmosphere, and 78% in the oceans. If the results found above (Arking 1996) are correct, then the partitioning is more like 33% and 67%. These results imply that a lot more energy is transported by the atmosphere than heretofore believed, and since things have to balance at the surface, one would expect less evaporation and precipitation in the models, since latent heat is the largest component in the atmosphere/surface energy exchange. Thus, the solar absorption discrepancy is important and should be further investigated.

  To test our conclusion, we will apply corrections to the solar fluxes in the GEOS-1 output data, that will mimic changes in the clear-sky radiative transfer code, and see if the resulting fluxes reproduce the statistical characteristics of the observations. If they do, then we can safely conclude that the discrepancy is a clear-sky effect. Then, in collaborating with colleagues Ming-Dah Chou and William Ridgway at GSFC, improved parameterizations of the solar radiation code will be developed and offered as a replacement to the existing code in the GEOS model.

6. Management

A new workstation (Sun Ultra 1 C3D m170E) was ordered in November for delivery in February 1996. It replaces the Sun 4/75 that has been used by the PI for the past 5 years. The new workstation will have 128 MB of RAM and 4.2 GB disk memory, which is double the present RAM and 3 times the present disk memory. We also added a 4 mm tape drive, with tape capacity of 5 MB, replacing the 1/4 inch drive with 250 MB capacity. Compute speed will increase by a factor of 10. The new workstation will enable us to handle the large data sets associated with GCM model output and to apply EOF and other statistical techniques without wasting manpower by breaking up the data into small sets, as was done up to now. In time, we expect to again double the RAM, bringing it to 256 MB. The old workstation will be moved to Johns Hopkins University for use by graduate students.

The PI level of effort continues at 50%. Due to very limited funding received in FY 95, no graduate students were assigned to the project during CY 1995. With the funding level approved for FY 96, a graduate research assistant will be assigned to this project beginning in the July-September 1996 time frame.

References

Arking, A., and D. Ziskin, 1994: Relationship between clouds and sea surface temperatures in the western tropical Pacific. *J. Climate*, 7, 988–1000.

Cess, R. D., M. H. Zhang, P. Minnis, L. Corsetti, E. G. Dutton, B. W. Forgan, D. P. Garber, W. L. Gates, J. J. Hack, E. F. Harrison, X. Jing, J. T. Kiehl, C. N. Long, J.-J. Morcrette, G. L. Potter, V. Ramanathan, B. Subasilar, C. H. Whitlock, D. F. Young, and Y. Zhou, 1995: Absorption of solar radiation by clouds: observations versus models. *Science*, 267, 496–499.

Chou, M.-D., A. Arking, J. Otterman, and W. L. Ridgway, 1995: The effect of clouds on atmospheric absorption of solar radiation. *Geophys. Res. Lett.*, 22, 1885–1888.

Lindzen, R. S., and S. Nigam, 1987: On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *J. Atmos. Sci.*, 44, 2418–2436.

Ohmura, A., and H. Gilgen, 1993: Re-evaluation of the global energy balance. *Interactions Between Global Climate Subsystems, the Legacy of Hann, Geophys. Momogr. No.* 75, IUGG v. 15, 93–110.

Pilewskie, P., and F. P. J. Valero, 1995: Direct observations of excess solar absorption by clouds. *Science*, 267, 1626–1629.

Ramanathan, V., and W. Collins, 1991: Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. *Nature*, 351, 27–32.

Ramanathan, V., B. Subasilar, G. J. Zhang, W. Conant, R. D. Cess, J. T. Kiehl, H. Grassl, and L. Shi, 1995: Warm pool heat budget and shortwave cloud forcing: a missing physics? *Science*, 267, 499–503.

Schubert, S. D., R. B. Rood, and J, Pfaendtner, 1993: An assimilated dataset for earth science applications. *Bull. Amer. Meteor. Soc.*, 74, 2331–2342.

Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I. Laszlo, A. Ohmura, H. Gilgen, T. Konzelman, R. C. DiPasquale, C. D. Moats, S. R. LeCroy, N. A. Ritchey, 1995: First global WCRP shortwave surface radiation budget dataset. *Bull. Amer. Meteor. Soc.*, 76, 905–922.